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Ahn et al.

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(54) **SYSTEMS, METHODS AND APPARATUSES
FOR HIGH POWER COMPLEMENTARY
METAL OXIDE SEMICONDUCTOR (CMOS)
ANTENNA SWITCHES USING BODY
SWITCHING AND EXTERNAL COMPONENT
IN MULTI-STACKING STRUCTURE**

6,788,957 B1 9/2004 Recouly et al.
6,836,172 B2 12/2004 Okashita

(Continued)

FOREIGN PATENT DOCUMENTS

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GB 2442848 A 4/2008

(Continued)

OTHER PUBLICATIONS

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Combined Search and Examination Report for GB0816744.7 mailed
Jan. 12, 2009.

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(Continued)

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(57) **ABSTRACT**

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455/278.1; 455/319

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455/83, 277.1, 278.1, 319
See application file for complete search history.

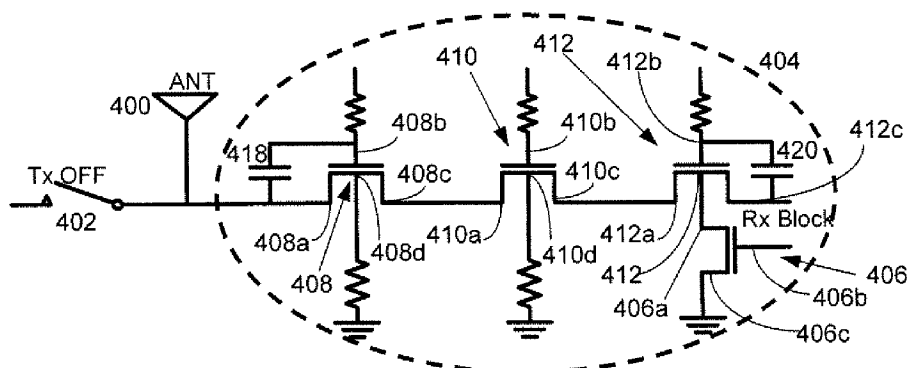
(56) **References Cited**

U.S. PATENT DOCUMENTS

5,461,265 A 10/1995 Kuniyama et al.
5,818,099 A 10/1998 Burgharz
6,094,088 A 7/2000 Yano
6,396,325 B2 5/2002 Goodell

Embodiments of the invention may provide for a CMOS antenna switch, which may be referred to as a CMOS SPDT switch. The CMOS antenna switch may operate at a plurality of frequencies, perhaps around 900 MHz, 1.9 GHz and 2.1 GHz according to an embodiment of the invention. The CMOS antenna switch may include both a receiver switch and a transmit switch. The receiver switch may utilize a multi-stack transistor with body substrate switching and attachment of external capacitor between drain and gate to block high power signals from the transmit path as well as to maintain low insertion loss at the receiver path. Exemplary embodiments of the CMOS antenna switch may provide for 38 dBm P_{0.1} dB at multi bands (e.g., 900 MHz, 1.8 GHz, and 2.1 GHz). In addition, -60 dBc second and third harmonic performance up to 30 dBm input, may be obtained according to example embodiments of the invention.

21 Claims, 13 Drawing Sheets



U.S. PATENT DOCUMENTS

6,882,829	B2	4/2005	Mostov et al.	
7,092,677	B1	8/2006	Zhang et al.	
7,233,775	B2	6/2008	De Graauw	
7,659,770	B2	2/2010	Teraguchi	
2003/0090313	A1	5/2003	Burgener et al.	
2004/0214535	A1	10/2004	Khorram	
2006/0119451	A1	6/2006	Chen	
2006/0199563	A1	9/2006	Kelly et al.	
2006/0252394	A1 *	11/2006	Suwa et al.	455/201
2007/0049237	A1	3/2007	Miura et al.	
2008/0079653	A1 *	4/2008	Ahn et al.	343/904
2008/0129642	A1 *	6/2008	Ahn et al.	343/876
2008/0247338	A1 *	10/2008	Kim et al.	370/280
2010/0001351	A1	1/2010	Zhang et al.	

FOREIGN PATENT DOCUMENTS

JP	08237166	A	9/1996
WO	9508868	A1	3/1995

OTHER PUBLICATIONS

"A high-power CMOS switch using a novel adaptive voltage swing distribution method in multistack FETs", IEEE Trans. on Microwave Theory and Techniques, vol. 56, No. 4, pp. 849-858, Apr. 2008.

"Design and analysis for a miniature CMOS SPDT switch using body-floating technique to improve performance", IEEE Transactions on Microwave Theory and Techniques, vol. 54 No. 1, pp. 31-39, Jan. 2006.

"Single-pole double-throw CMOS switches for 900-MHz and 2.4-GHz applications on p- silicon substrates", IEEE Journal of Solid-State Circuits, vol. 39, No. 1, pp. 35-41, Jan. 2004.

United Kingdom International Search Report for GB0719303.0 dated Jan. 24, 2008.

United Kingdom International Search Report for GB0710606.5, dated Sep. 27, 2007.

Office Action dated Jan. 19, 2010 for German Patent Application No. 102008046778.2.

Karl Goser, Großintegrationstechnik - Teil 1: Vom Transistor zur Grundschialtung. Heidelberg: Hüthig, 1990, S. 99-10. ISBN: 3-7785-1615-9.

Non-Final Office Action dated Mar. 24, 2010 for Application No. 11/943,378.

Non-Final Office Action dated Jan. 26, 2010 for Application No. 11/857,322.

* cited by examiner

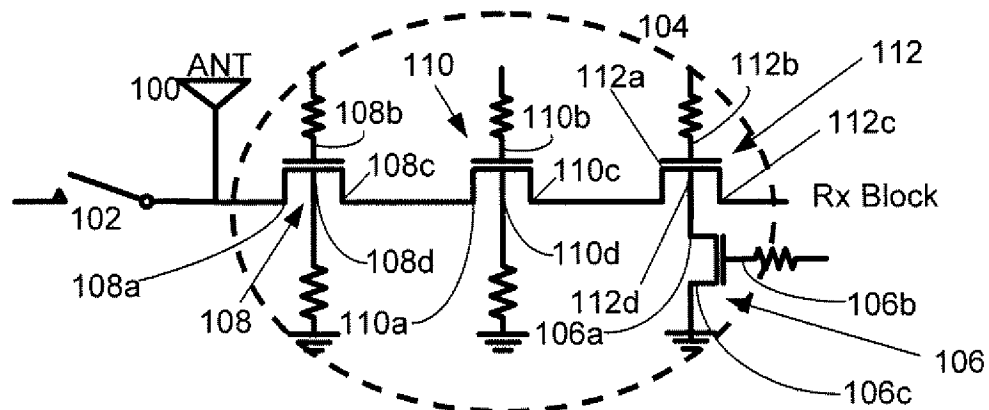


FIG. 1A

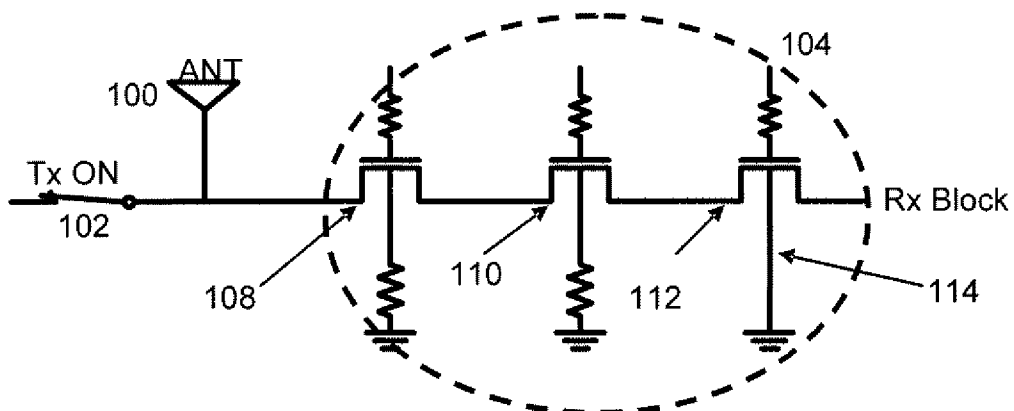


FIG. 1B

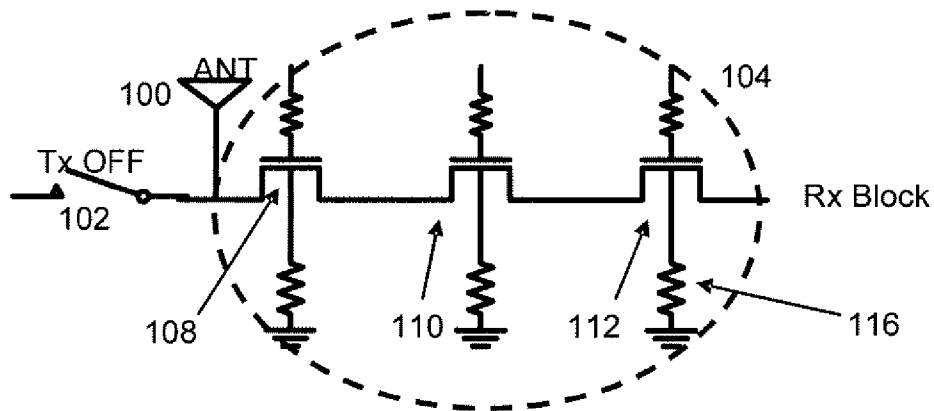


FIG. 1C

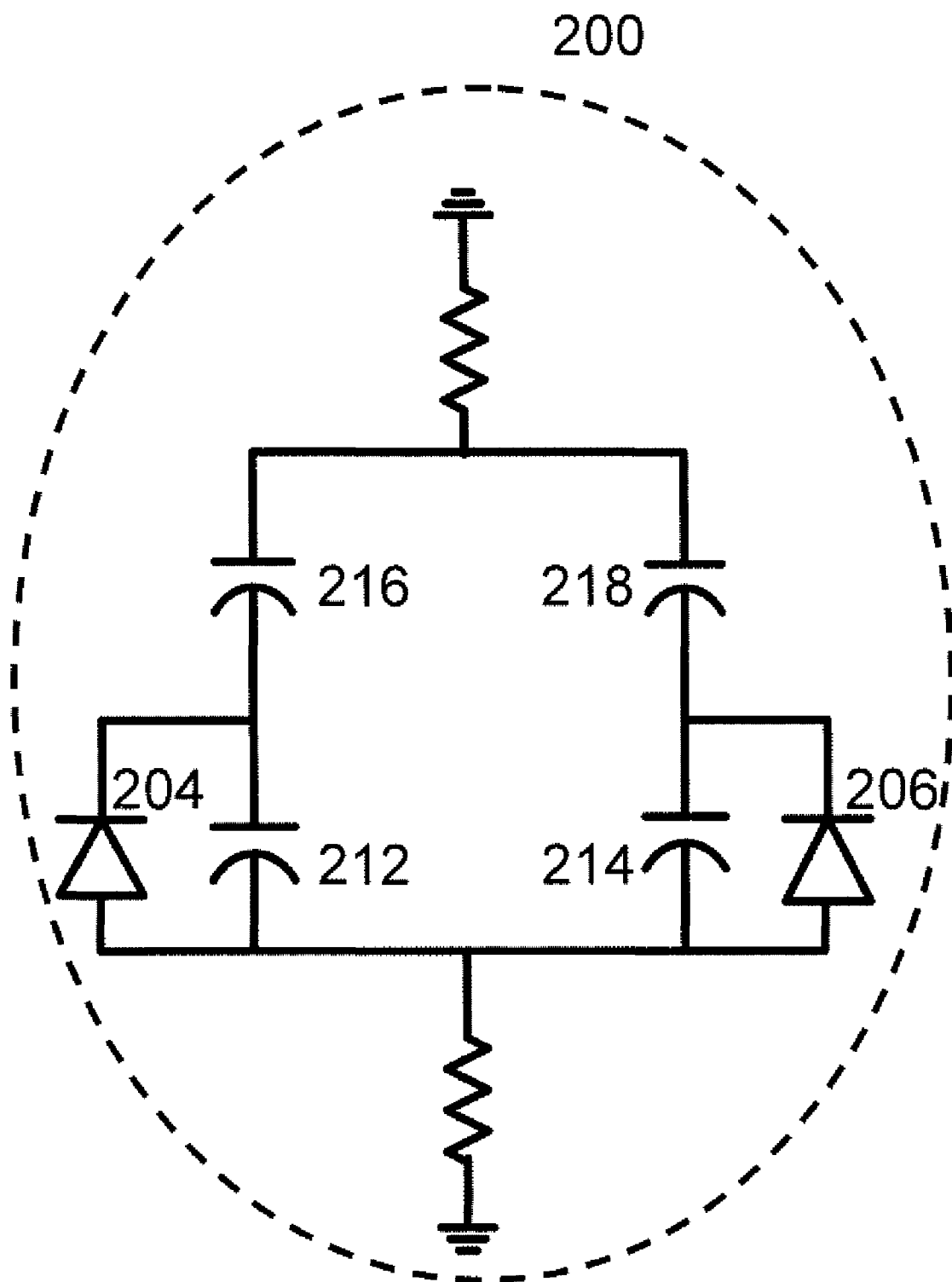


FIG. 2A

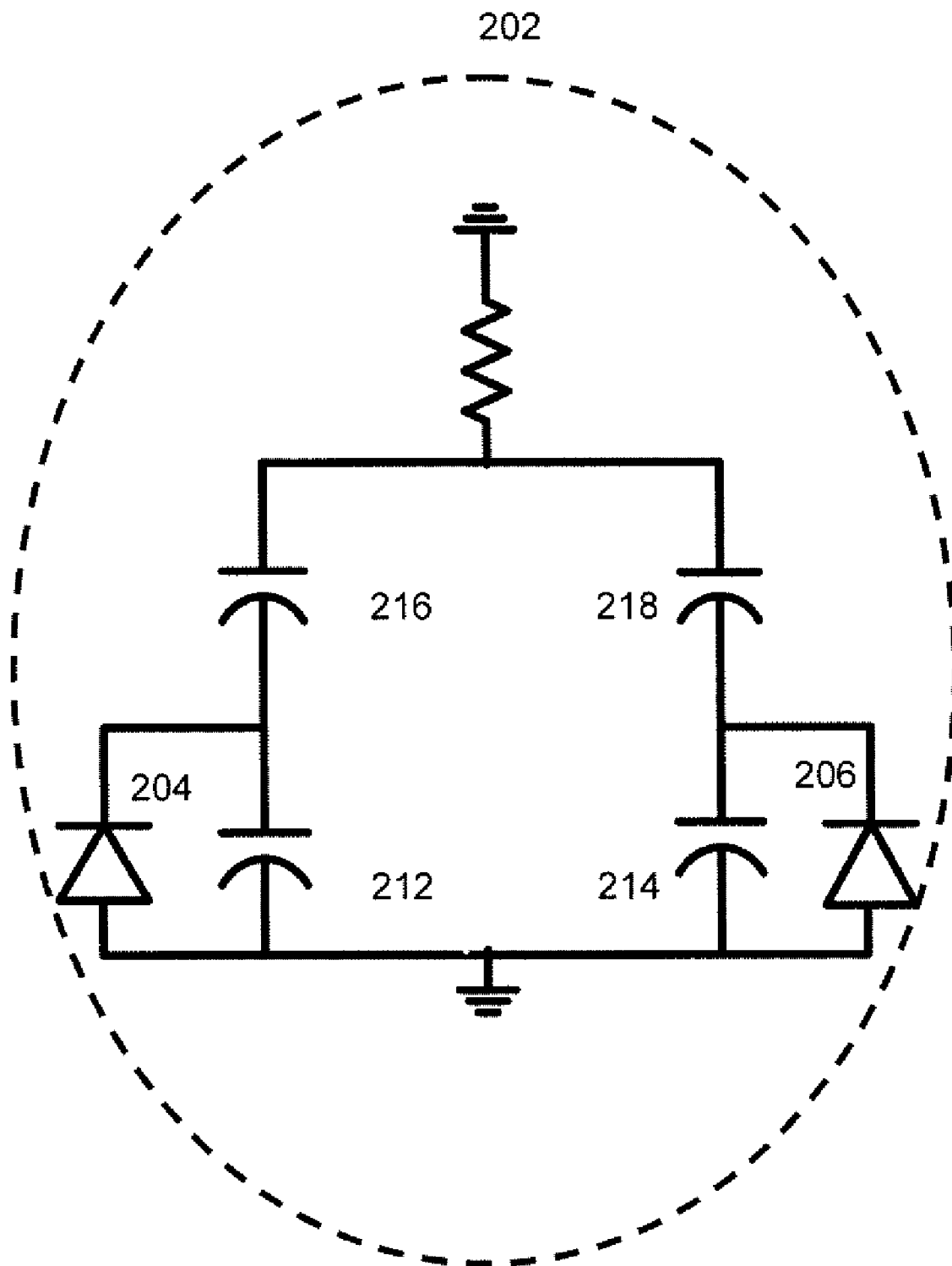


FIG. 2B

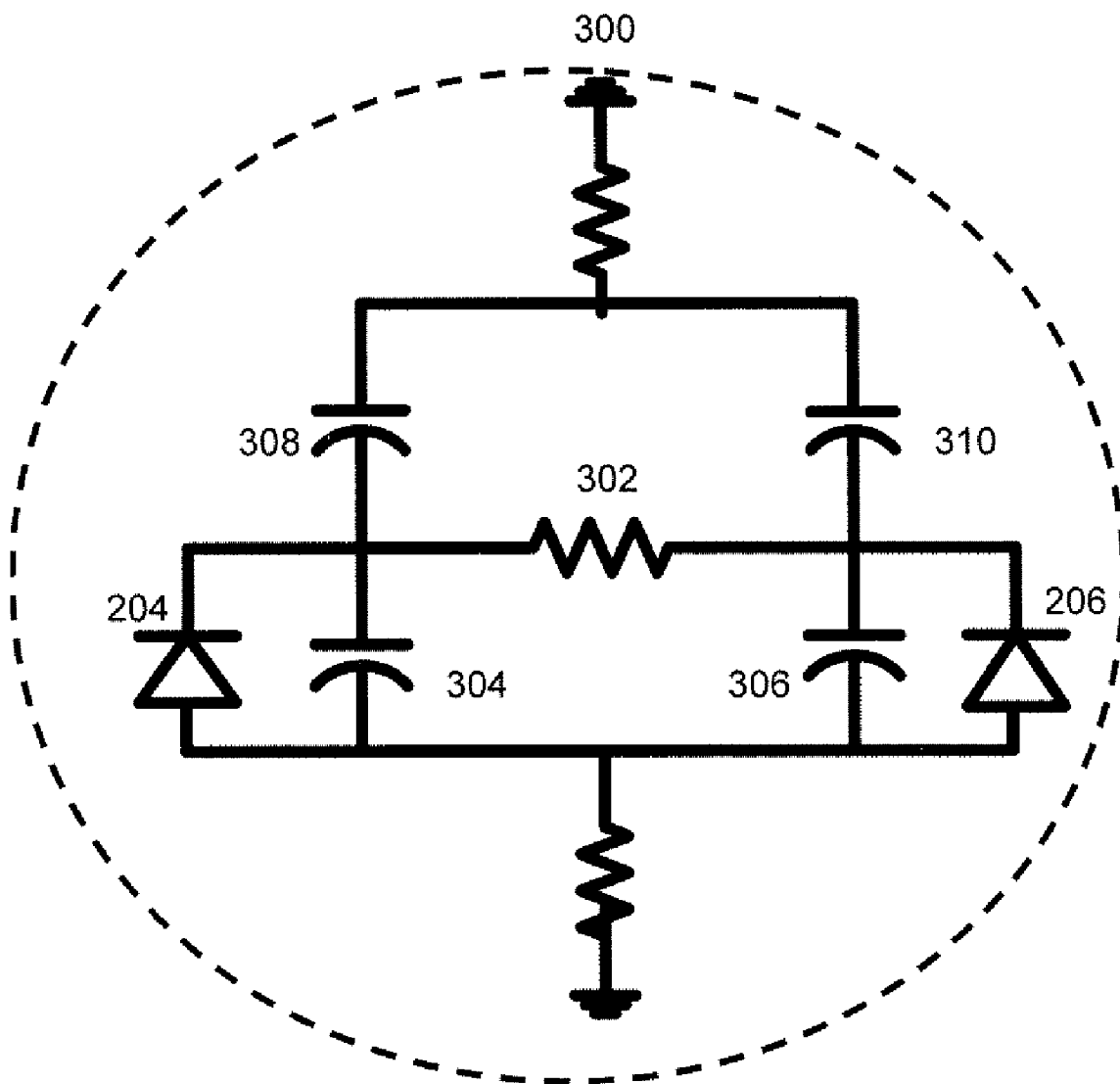


FIG. 3

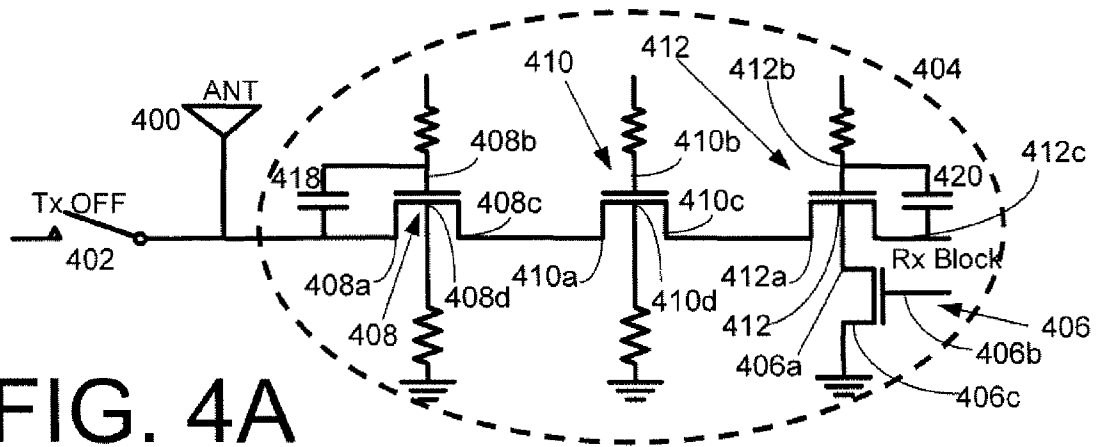


FIG. 4A

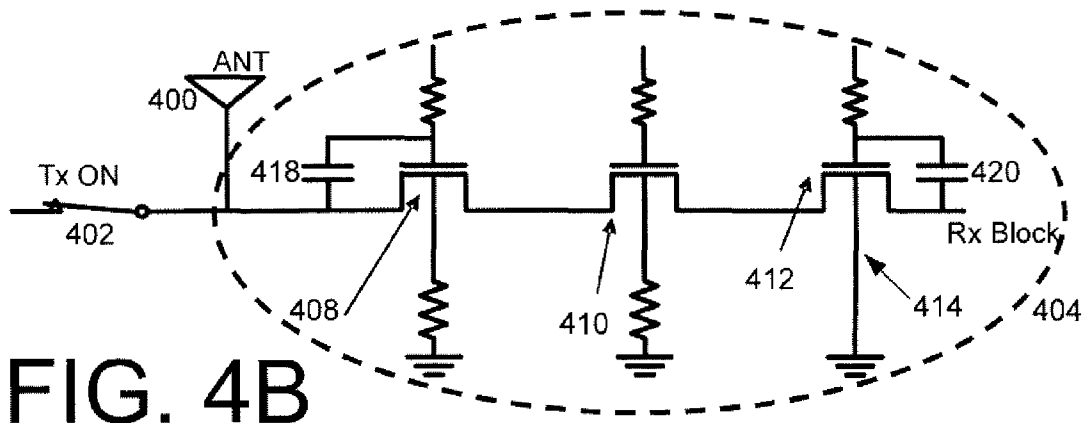


FIG. 4B

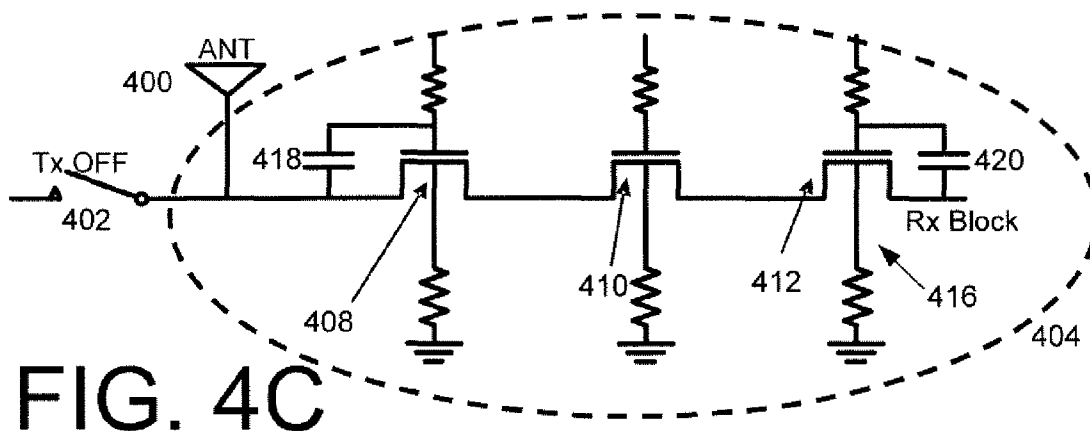


FIG. 4C

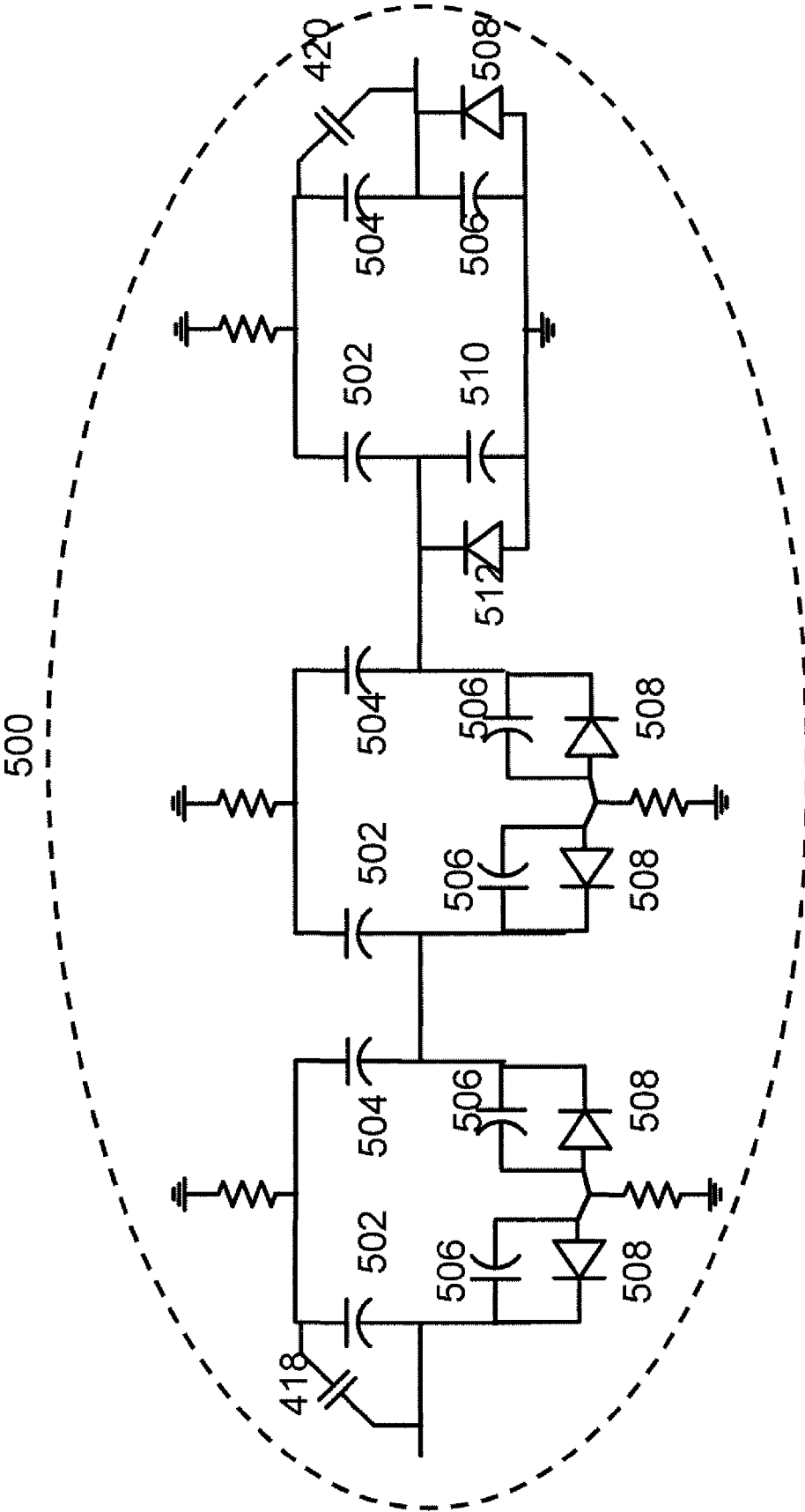


FIG. 5

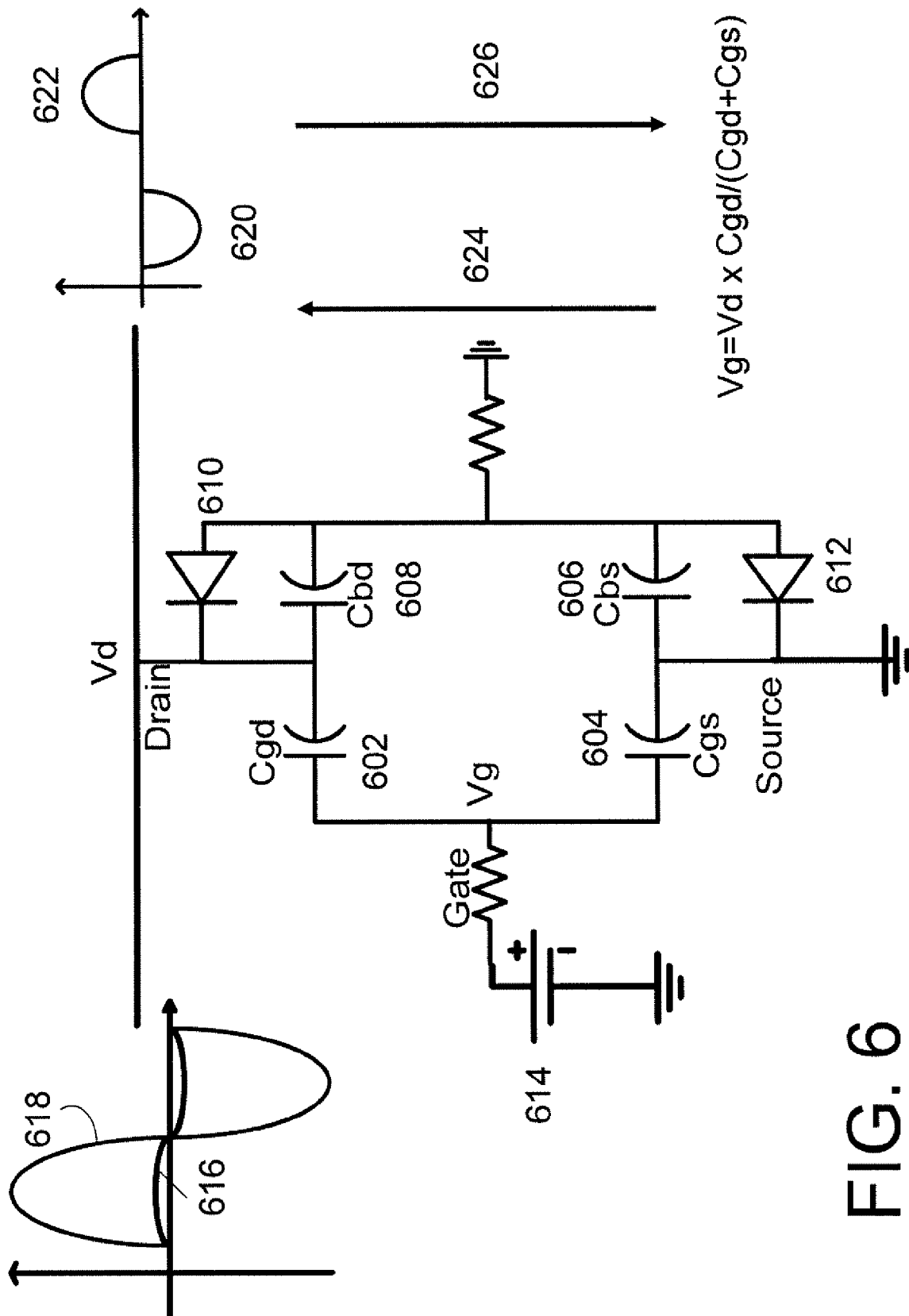


FIG. 6

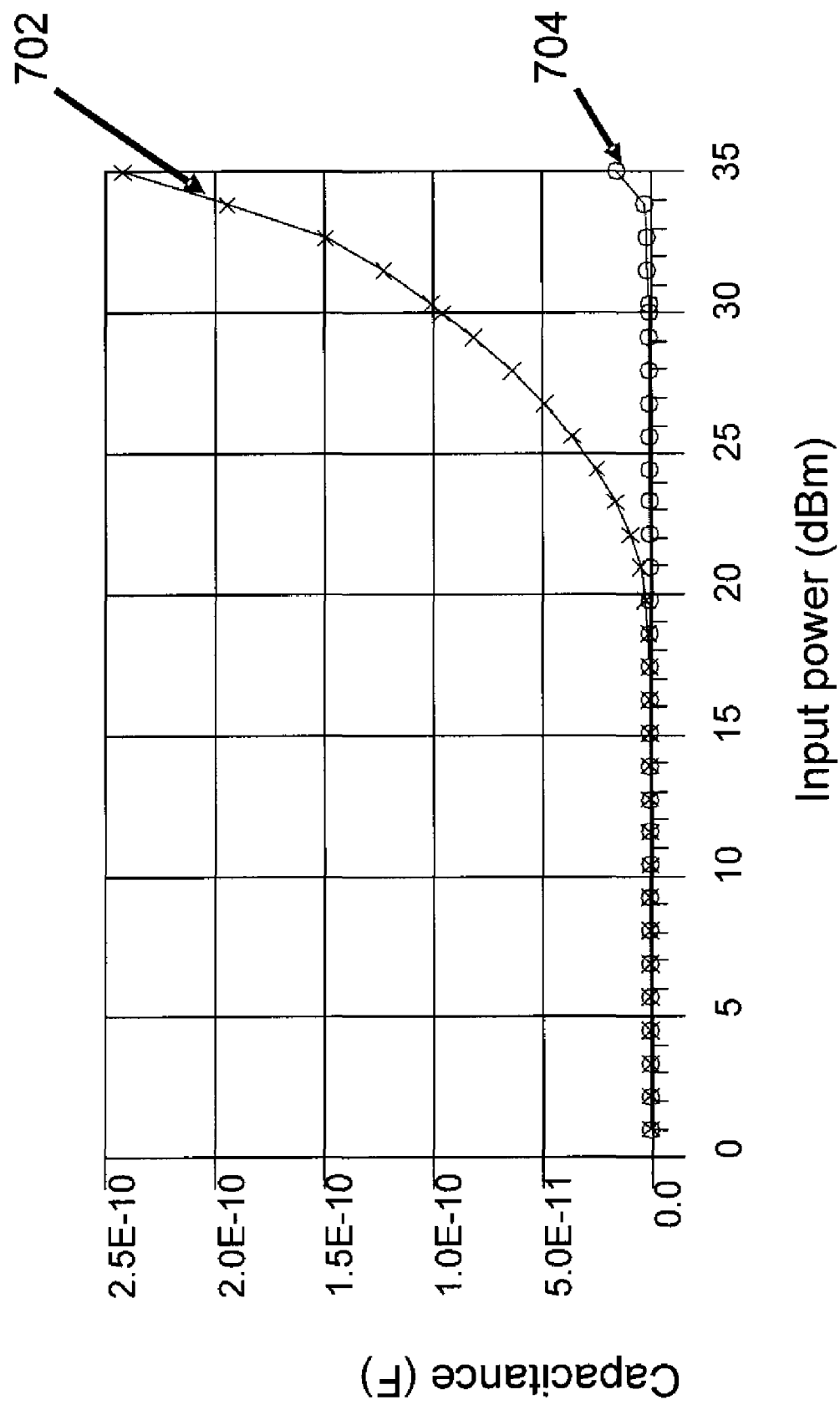
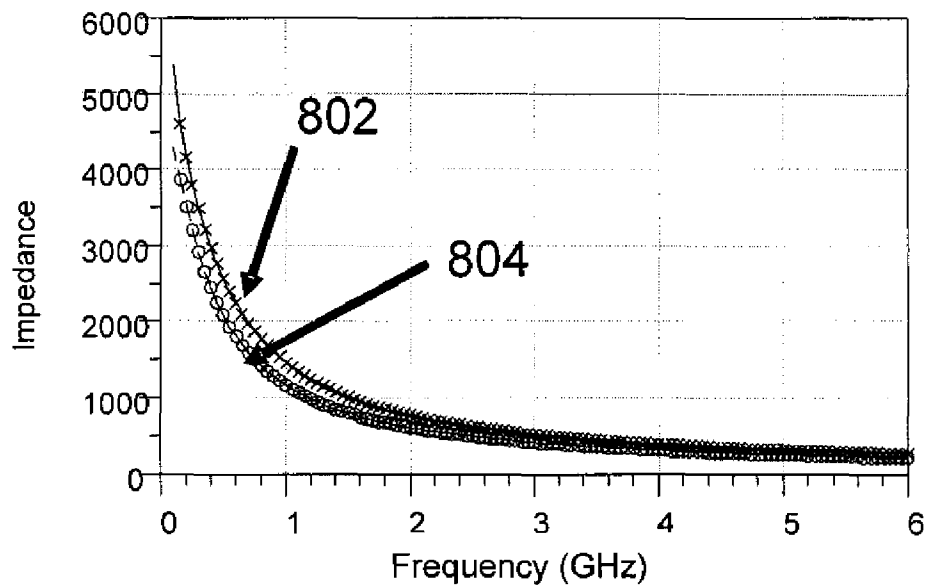
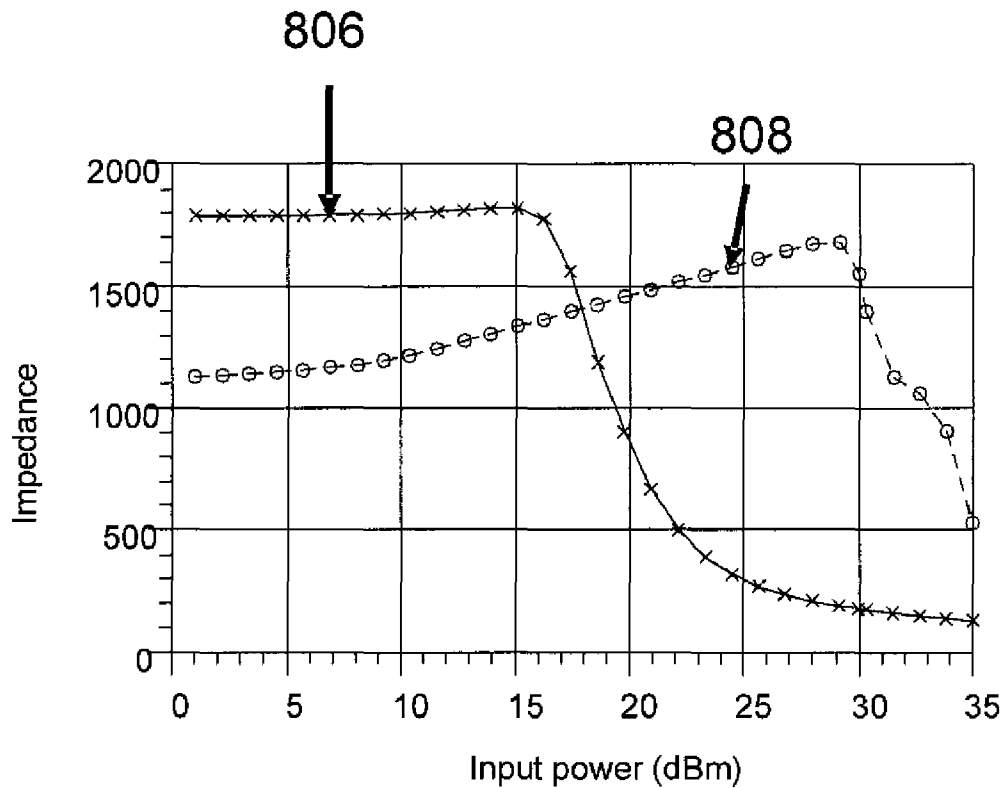


FIG. 7

**FIG. 8A****FIG. 8B**

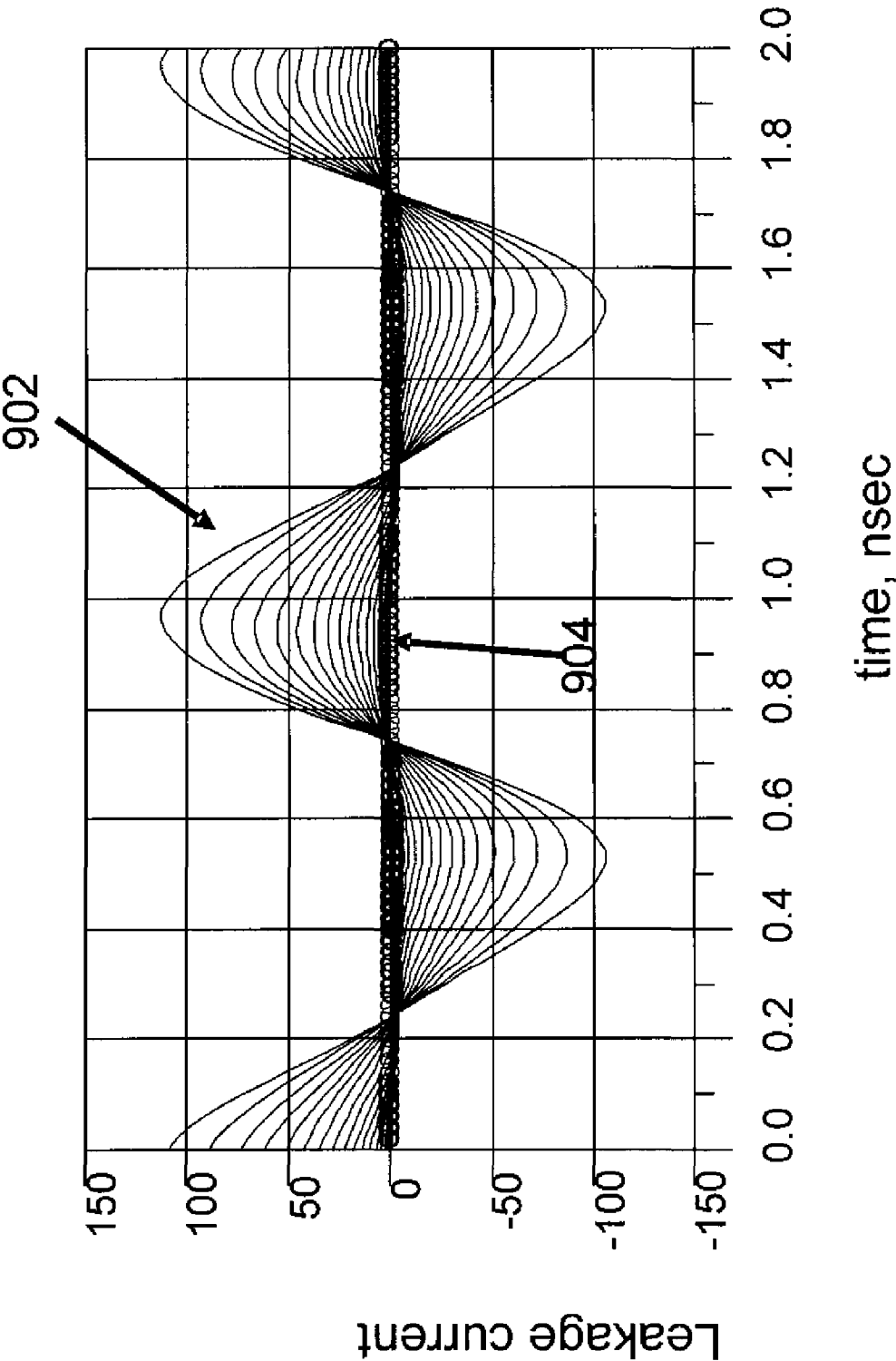


FIG. 9

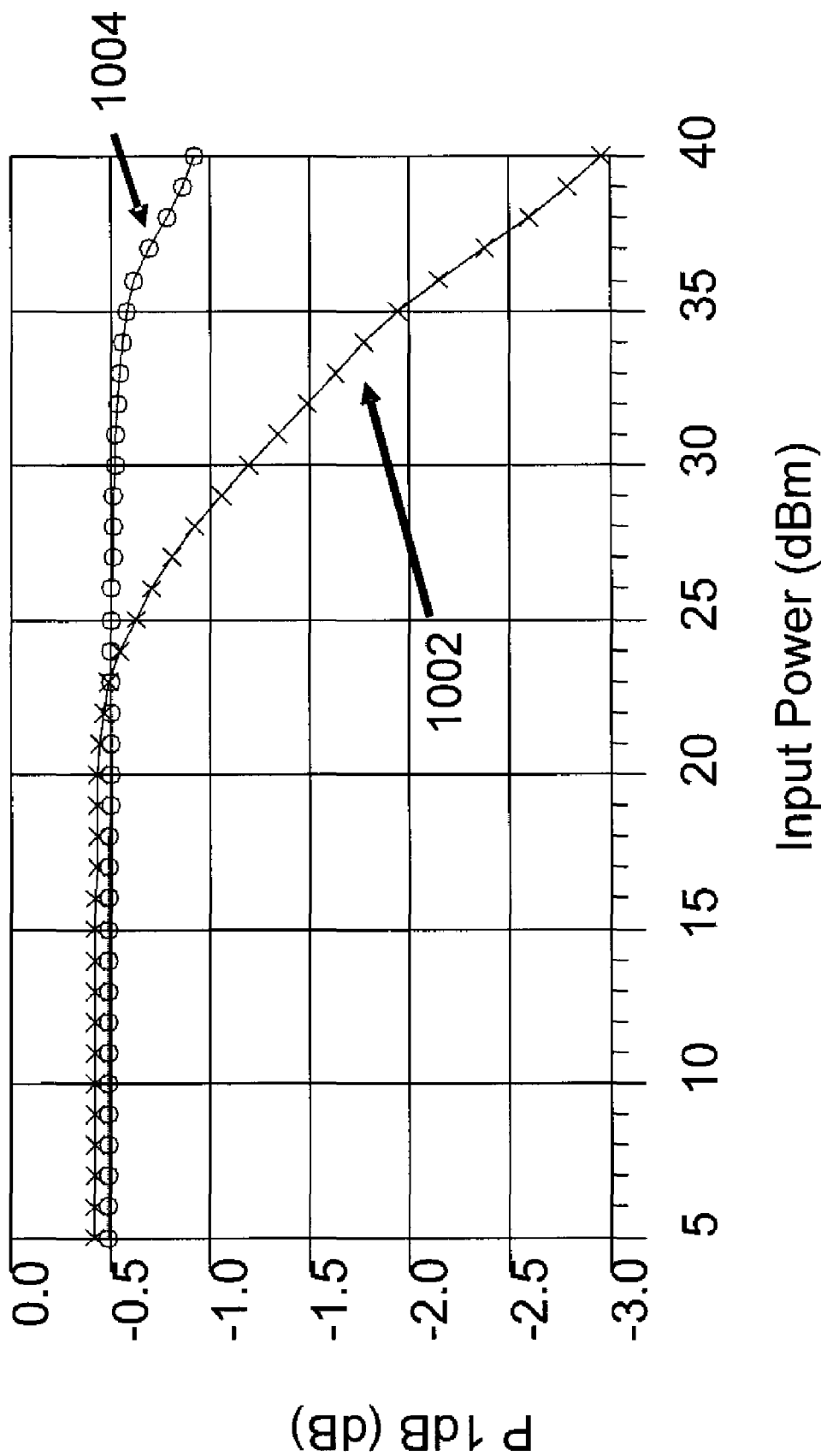


FIG. 10

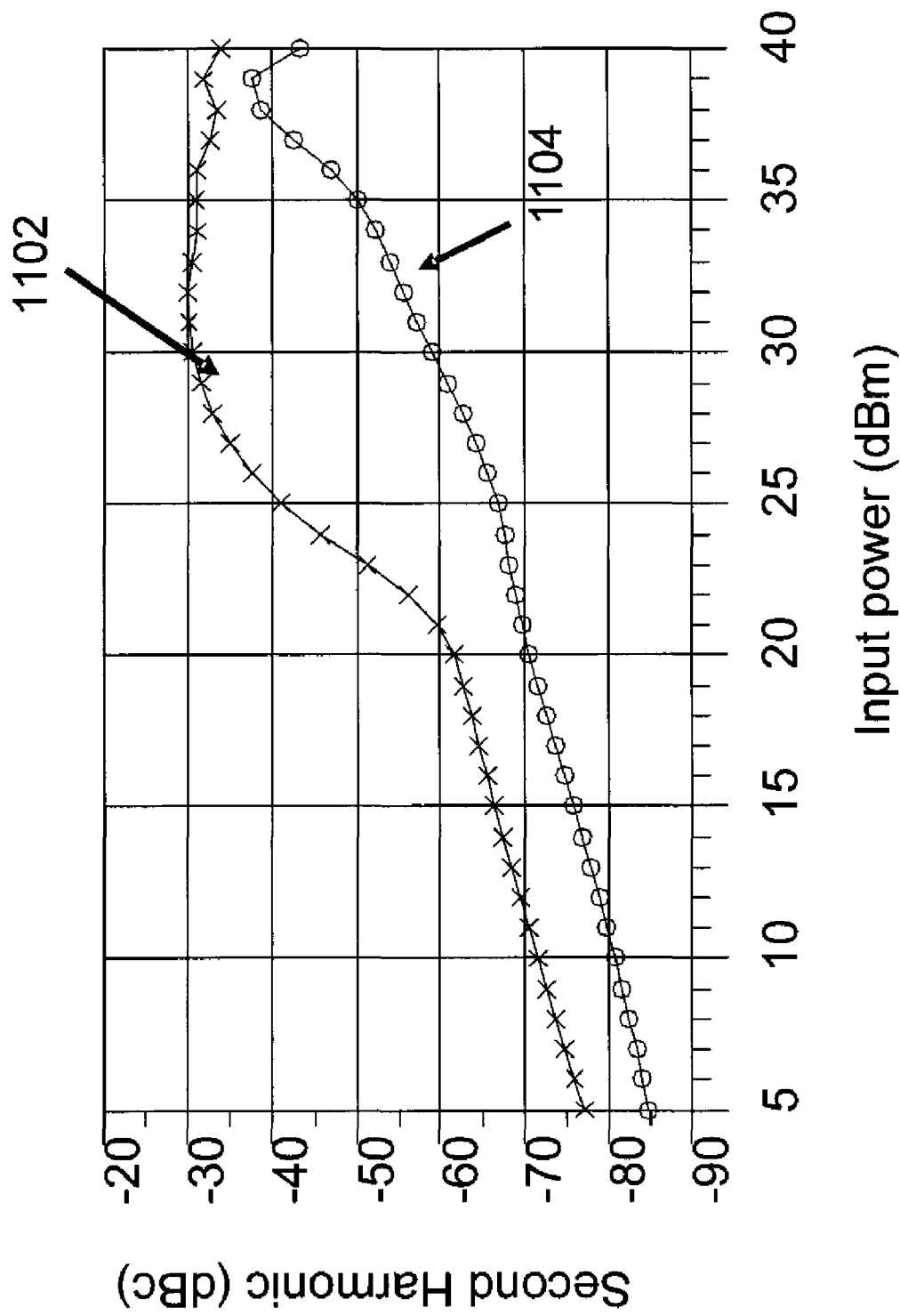


FIG. 11

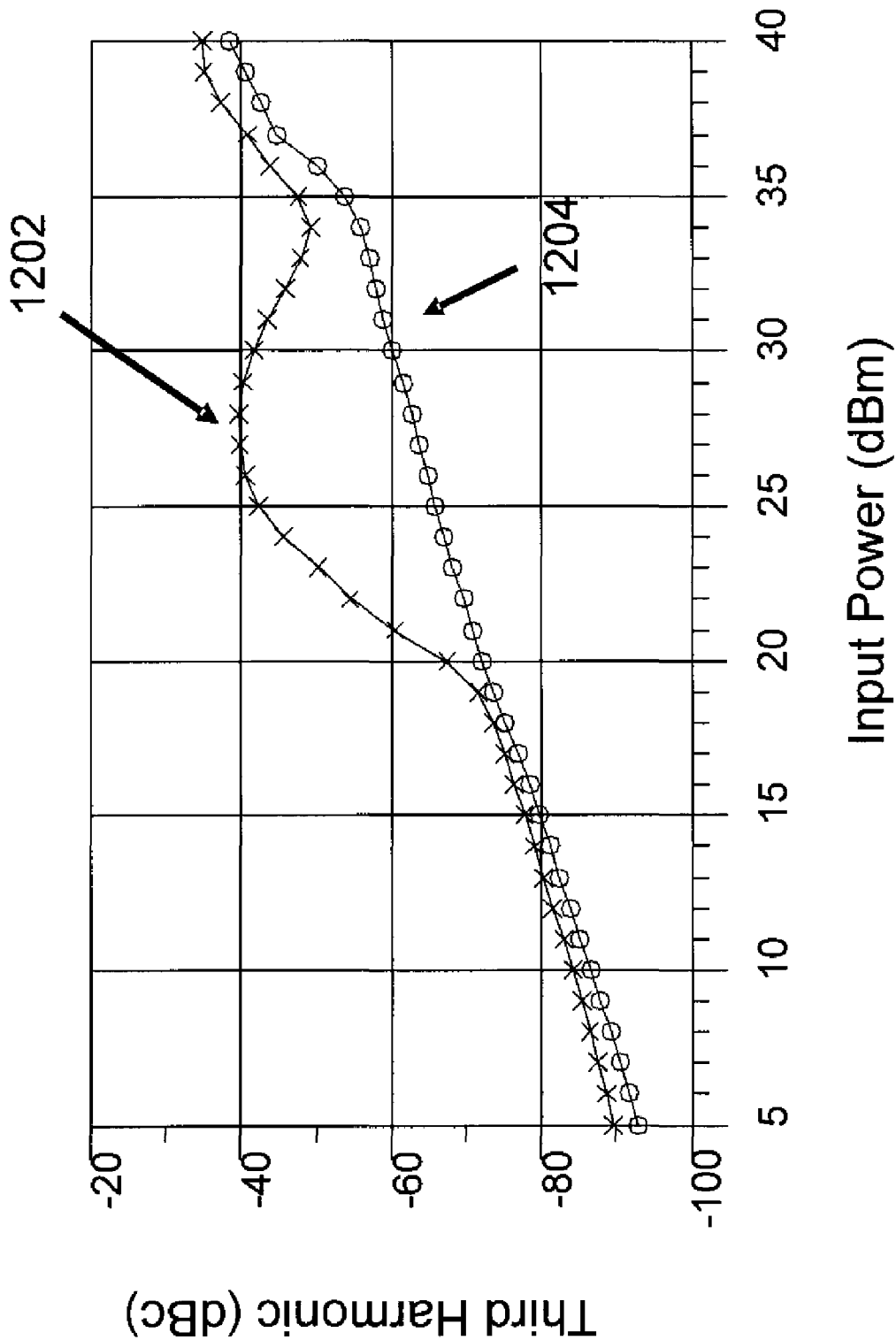


FIG. 12

1

**SYSTEMS, METHODS AND APPARATUSES
FOR HIGH POWER COMPLEMENTARY
METAL OXIDE SEMICONDUCTOR (CMOS)
ANTENNA SWITCHES USING BODY
SWITCHING AND EXTERNAL COMPONENT
IN MULTI-STACKING STRUCTURE**

FIELD OF THE INVENTION

The invention relates generally to antenna switches, and more particularly, to CMOS (complementary metal oxide semiconductor) antenna switches.

BACKGROUND OF THE INVENTION

In the past decade, the wireless communication industry has experienced explosive growth, which has in turn accelerated the development of integrated circuit (IC) industry. In particular, in the IC industry, many mobile application systems like low noise amplifiers (LNAs), mixers, and voltage-controlled oscillators (VCOs) have been integrated into CMOS technology. Two significant mobile application components—power amplifiers (PAs) and radio frequency (RF) switches—have not yet been commercially integrated into CMOS technology.

However, IC industry research is quickly moving towards power amplifier integrated into CMOS technology. For example, current research indicates that a CMOS power amplifier may be feasible and be able to provide a significant amount of power, perhaps up to 2 W, for mobile communications. Accordingly, when the power amplifier becomes integrated into CMOS technology, there will be a need for an RF switch integrated into CMOS technology.

However, current CMOS technology presents a variety of difficulties for its application to RF switches. In particular, CMOS material characteristics, including lossy substrates due to low mobility of electrons and low breakdown voltages due to p-n junction, hot carrier effects, have prevented CMOS technology from being used for RF switches that require multi-band operation, high power levels, and/or integration with other devices and circuits.

BRIEF SUMMARY OF THE INVENTION

Embodiments of the invention may provide for CMOS RF switches, which may be referred to as a CMOS SPDT switch. According to an embodiment of the invention, the CMOS RF switch may be fabricated using a standard 0.18 μm process, although other processes may be utilized without departing from the embodiments of the invention. In order to provide high-power handling capability in a multi-band operation (e.g., about 900 MHz, 1.9 GHz and 2.1 GHz) of the CMOS RF switch, a multi-stacked transistor with substrate body switching may be applied to the receiver switch. According to an embodiment of the invention, the CMOS RF switch may provide higher power blocking capability and lower leakage current toward the receiver switch at the transmission (Tx) mode as well as low insertion loss at the reception (Rx) mode at multi-band (e.g., 900 MHz, 1.9 GHz and 2.1 GHz).

According to an example embodiment of the invention, there is a CMOS antenna switch. The CMOS antenna switch may include an antenna operative at a plurality of radio frequency (RF) bands, a transmit switch in communication with the antenna, and a receiver switch in communication with the antenna, where the receiver switch comprises a plurality of transistors. The CMOS antenna switch may also include a first external component provided for a first transistor of the

2

plurality of transistors, where the first transistor includes a first source and a first gate, and wherein the first external component connects the first source and the first gate, and a second external component provided for a second transistor of the plurality of transistors, where the second transistor includes a second gate, a second drain, and a second body substrate, where the second external component connects the second gate and the second drain, and where the second body substrate is selectively connectable between a resistance and ground.

According to another example embodiment of the invention, there is a method for a CMOS antenna switch. The method may include providing an antenna operative at a plurality of radio frequency (RF) bands, electrically connecting a transmit switch and a receiver switch to the antenna, where the receiver switch comprises a plurality of transistors, and providing a first external component for a first transistor of the plurality of transistors, where the first transistor includes a first source and a first gate, and wherein the first external component connects the first source and the first gate. The method may also include providing a second external component for a second transistor of the plurality of transistors, where the second transistor includes a second gate, a second drain, and a second body substrate, where the second external component connects the second gate and the second drain, and where the second body substrate is selectively connectable between a resistance and ground.

According to yet another embodiment of the invention, there is a CMOS antenna switch. The CMOS antenna switch may include an antenna operative at a plurality of radio frequency (RF) bands, a transmit switch in communication with the antenna, and a receiver switch in communication with the antenna, where the receiver switch includes a plurality of transistors, including a first transistor having a first source and a first gate, and a second transistor having a second gate, a second drain, and a second body substrate. The CMOS antenna switch may also include means for electrically connecting the first source and the first gate, means for electrically connecting the second gate and the second drain, and means for selectively connecting the second body substrate between a resistance and ground.

**BRIEF DESCRIPTION OF THE SEVERAL
VIEWS OF THE DRAWING(S)**

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

FIGS. 1A, 1B and 1C illustrate simplified example operations of a receiver switch utilizing an example body switching technique in accordance with an example embodiment of the invention.

FIG. 2A illustrates an equivalent lumped model of a body floating transistor at an OFF state, according to an example embodiment of the invention.

FIG. 2B illustrates an equivalent lumped model of a body grounded transistor at OFF state, according to an example embodiment of the invention.

FIG. 3 illustrates an equivalent lumped model of body floating transistor at ON state, according to an example embodiment of the invention.

FIGS. 4A, 4B and 4C illustrate simplified example operations of a receiver switch in accordance with example embodiments of the invention.

FIG. 5 illustrates an equivalent lumped model of a multi-stack structure of a receiver switch utilizing a body switching

technique and external components such as capacitors, according to an example embodiment of the invention.

FIG. 6 illustrates a turn-on mechanism of a switch in the OFF state when a high-power signal is applied, according to an example embodiment of the invention.

FIG. 7 illustrates an example of receiver switch simulation results in terms of capacitance of OFF state device as a function of input power level, according to an example embodiment of the invention.

FIG. 8A illustrates an example of receiver switch simulation results in terms of impedance of OFF state device, according to an example embodiment of the invention.

FIG. 8B illustrates an example of receiver switch simulation results in terms of impedance of OFF state device, according to an example embodiment of the invention.

FIG. 9 illustrates an example of receiver switch simulation results in terms of leakage current toward receiver, according to an example embodiment of the invention.

FIG. 10 illustrates an example of transmit switch simulation results in terms of power handling capability, according to an example embodiment of the invention.

FIG. 11 illustrates an example of transmit switch simulation results in terms of second harmonic performance, according to an example embodiment of the invention.

FIG. 12 illustrates an example of transmit switch simulation results in terms of third harmonic performance, according to an example embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, these inventions may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

Embodiments of the invention may provide for CMOS RF antenna switches, which may also be referred to as SPDT CMOS switches. The CMOS RF antenna switches in accordance with embodiments of the invention may provide for one or more of multi-band operation, high power handling, and integration with other devices and circuits. Generally, the CMOS RF antenna switch may include a receiver switch and a transmit switch. The receiver switch may utilize one or more switching substrate bodies and external components such as capacitors between drain-gate and source-gate in a multi-stack structure, which will be described in further detail below. In addition, the transmit switch may utilize a substrate body tuning technique, as will also be described in further detail below.

I. A First Embodiment of CMOS RF Antenna Switch

A CMOS RF antenna switch in accordance with an embodiment of the invention will now be described with reference to FIGS. 1-3. It will be appreciated that while a particular embodiment of the CMOS RF antenna switch is illustrated in FIGS. 1-3, other variations of the illustrated CMOS RF antenna switch are available without departing from an embodiment of the invention.

FIG. 1A illustrates a simplified CMOS RF antenna switch and its operation in accordance with an example embodiment of the invention. The CMOS RF antenna switch may include a transmit switch **102** and a receiver switch **104**, in accordance with an example embodiment of the invention. Additionally, CMOS RF antenna switch may include an antenna

100 that is in communication with at least one of the transmit switch **102** and the receiver switch **104**. According to an example embodiment of the invention, the antenna **100** may be a single multi-mode (e.g., RX and TX), multi-band antenna, although a plurality of distinct antennas may be utilized according to other embodiments of the invention. The receiver switch **104** may be comprised of cascaded or stacked transistors **108**, **110**, **112**, and **106**, which may be Complementary Metal Oxide Semiconductor (CMOS) transistors, according to an example embodiment of the invention. The transistor **108** may include a source **108a**, a gate **108b**, a drain **108c**, and a body substrate **108d**. The transistor **110** may include a source **110a**, a gate **110b**, a drain **110c**, and a body substrate **110d**. The transistor **112** may include a source **112a**, a gate **112b**, a drain **112c**, and a body substrate **112d**. The transistor **106** may include a source **106a**, a gate **106b**, a drain **106c**, and a body substrate (not shown).

The transistor **108** may have its drain **108c** connected to the source **110a** of transistor **110**. In addition, the transistor **110** may have its drain **110c** connected to the source of transistor **112a**. The drain **112c** of transistor **104** may be connected to the receive (RX) block to processes received signals from the antenna **100**. Additionally, the body substrate **112a** of the transistor **112** may be connected to the source **106a** of the transistor **106**. The drain **106c** of the transistor **106** may be connected to ground. As will be described in further detail, at least one transistor **106**, which may operate as a substrate body switch for transistor **112**, may be provided at the substrate body **112d** in accordance with an example body switching technique. In particular, the at least one transistor **106** may be switched to an ON state or an OFF state, depending on whether depending on whether a respective transmit (Tx) mode or receive (Rx) mode is in operation. As will be described in further detail below in accordance with an example embodiment of the invention, the receiver switch **104** of FIG. 1A may yield different equivalent circuits depending on whether the receiver switch **104** is in an OFF state, as illustrated in FIG. 1B, or an ON state, as illustrated in FIG. 1C.

A. Transmit Mode

FIG. 1B illustrates an equivalent circuit of the receiver switch **104** in an OFF (e.g., disabled, block, etc.) state, according to an example embodiment of the invention. In FIG. 1B, the receiver switch **104** may be placed in the OFF state in order to provide isolation from the transmit switch **102**. With the receiver switch **104** in the OFF state, a transmit signal may be provided from a transmit (Tx) block to the antenna **100**. As shown in FIG. 1B, when the receiver switch **104** is in an OFF state, the stacked transistors **108**, **110**, **112** may then be placed in an OFF state (e.g., opened), thereby providing a higher impedance. The stacked transistor **106** may be placed in an ON state **114** (e.g., closed), thereby shorting the substrate body **112d** of transistor **112** to ground, and reducing the signal paths for leakage current to travel from source **112a** to drain **112c**.

In the configuration of FIG. 1B, the power of the transmit (Tx) signal may be maximized (and maximizing the power handling capability of the Tx block). The power handling capability of the transmit switch **102** may be determined by controlling leakage current directed towards the OFF-state receiver switch **104** as well as the source-to-drain breakdown voltage of cascaded switches **108**, **110**, and **112** of the receiver switch **104**. Thus, the maximum transmit power of the transmit switch **102** may be dependent upon the characteristics of the receiver switch **104**.

It will be appreciated that in order to increase the power handling capability of the Tx switch **102**, the number of

5

multi-stacked transistors **108**, **110**, **112** may be increased to reduce the breakdown burden of each transistor **108**, **110**, **112**. For example, more than three transistors **108**, **110**, and **112** may be cascaded, according to another embodiment of the invention. Furthermore, it will be appreciated that the last transistor **112** from the antenna **112** can control leakage current at the receiver switch **104**. If the leakage current toward OFF-state switches **108**, **110**, and **112** in the Rx path is minimized, then maximum power may be delivered from the Tx block to the antenna **100**. As described above, the body switching transistor **106** that is connected between ground and the body substrate **112d** of transistor **112** may be used to control leakage current at the receiver switch **104**. More particularly, by placing the body switching transistor **106** in the ON state **114**, the substrate body **112d** of the last transistor **112** from the antenna **100** to the Rx block can be grounded, thereby reducing the signal paths for leakage current to travel from source **112a** to drain **112c**.

Still referring to FIG. 1B, when the receiver switch **104** is in the OFF position, the stacked transistors **108**, **110** may be body-floating transistors while stacked transistor **112** may be a body-grounded transistor. FIG. 2A illustrates an equivalent lumped model of a body floating transistor at an OFF state **200** such as transistors **108**, **110** in FIG. 1B, according to an example embodiment of the invention. FIG. 2B illustrates an equivalent lumped model of a body grounded transistor at an OFF state **202** such as transistor **112** in FIG. 1B, according to an example embodiment of the invention. The equivalent models in FIGS. 2A and 2B include capacitors **212**, **214**, **216**, **218** as well as p-n junction diodes **204**, **206**, according to an example embodiment of the invention.

When a voltage swing at the antenna **100** is received by the receiver switch **104**, the voltage swing may be divided among stacked transistors **108**, **110**, and **112**. Accordingly, the last transistor **112** may only experience only one third of the full voltage swing at the antenna, thereby reducing the possibility of a source-to-drain breakdown voltage occurring for transistor **112**. It will be appreciated, however, that the voltage swing at the last transistor **112** may be different, and perhaps smaller, if additional preceding transistors are provided according to other embodiments of the invention to reduce the burden of the stacked transistors **108**, **110**, **112**.

The transistors **108**, **110** may be body floating transistors, as illustrated in FIG. 2A. However, in order to reduce the leakage current towards the Rx block and maximize the power handling of the Tx block to the antenna **100**, the body switching transistor **106** can be put in the ON position **114** to connect the substrate body **112d** to ground. Accordingly, the transistor **112** may be a body grounded transistor, as illustrated in FIG. 2B, which reduces the signal paths for leakage current to travel from source **112a** to drain **112c**.

When a negative voltage swing is applied to the receiver switch **104**, the p-n junction diodes **204**, **206** of the transistor **112** may turn on so that leakage current may occur by the current passing through the p-n junction diodes **204**, **206**. An issue with the p-n junction diode **204**, **206** turning on may be the possible clipping of the negative voltage swing so that power handling capability of the Tx block to the antenna **100** can be limited. However, this leakage current generated by channel formation of the device **112** in OFF state is prevented because the voltage level at **112a** is fixed by the turning on voltage of the p-n junction diode **204**. Indeed, the multi-stacked transistors **108**, **110**, and **112** at OFF-state can divide the voltage swing at antenna port so that the last OFF-state transistor **112**, and thus, p-n junction diodes **204**, **206**, may experience only one third of voltage swing at antenna **100**.

6

Thus, the overall voltage swing at antenna port may not be sufficient to turn the p-n junction diodes **204**, **206** on at the last transistor **112**.

B. Receive Mode

FIG. 1C illustrates an equivalent circuit of the receiver switch **104** in an ON (e.g., enable, receive, etc.) state, according to an example embodiment of the invention. In FIG. 1C, the receiver switch **104** may be placed in the ON position in order for the receive (RX) block to receive a signal from the antenna **100**. With the receiver switch **104** in the ON state, the transmit switch **102** may be placed in the OFF (e.g., disabled, block) state to isolate the transmit switch **102** from the receiver switch **104**. As shown in FIG. 1C, when the receiver switch **104** is in an ON state, the stacked transistor **106** may be placed in an OFF state **116**, thereby providing an equivalent resistor between the body substrate **112d** of transistor **112** and ground (i.e., body floating). In this way, the insertion loss at the receive (Rx) path from the antenna **100** to the RX block may be minimized.

FIG. 3 illustrates an equivalent lumped model of body floating transistor at ON state **300**, according to an example embodiment of the invention. As described above, the transistor **106** may be provided in an OFF position **116** to provide a body floating transistor, as illustrated by the equivalent lumped model of FIG. 3. In FIG. 3, as the size of the transistor **112** increases, the parasitic capacitors **304**, **306**, **308**, **310** may provide another signal path at the ON **300** state. More specifically, the ON state transistor of FIG. 3 may have an ON-resistor **302**, a gate-drain capacitor **308** to gate-source capacitor **310**, and a drain-body capacitor **304**, and body-source capacitor **306** as signal paths. If the body substrate were grounded, then one of these signal paths through capacitors **304**, **306** may be lost, thereby increasing the insertion loss. Accordingly, when the receiver switch **104** is in the ON state, the last transistor **112** need to be in body floating state (e.g., with transistor **106** in the ON state **116**) to ensure minimized insertion loss.

II. A Second Embodiment of a CMOS RF Antenna Switch

An alternative embodiment of a CMOS RF antenna switch with additional power handling capability will now be discussed with reference to FIGS. 4A-6. Generally, the CMOS RF antenna switch with improved power handling capability may include external components such as capacitors for improving the power handling of the CMOS antenna switch.

Referring to FIG. 4A, the CMOS RF antenna switch may include a transmit switch **402** and a receiver switch **404**. Further, an antenna **400** may be provided that is in communication with at least one of the transmit switch **402** and the receiver switch **404**. The receiver switch **404** may include stacked transistors **408**, **410**, **412**, and **406**, which may be complementary metal oxide semiconductor (CMOS) transistors, according to an example embodiment of the invention. The receiver switch **404** may further include capacitors **418**, **420**. The transistor **408** may include a source **408a**, a gate **408b**, a drain **408c**, and a body substrate **408d**. The transistor **410** may include a source **410a**, a gate **410b**, a drain **410c**, and a body substrate **410d**. The transistor **412** may include a source **412a**, a gate **412b**, a drain **412c**, and a body substrate **412d**. The transistor **406** may include a source **406a**, a gate **406b**, a drain **406c**, and a body substrate (not shown).

As shown in FIG. 4A, an external component such as a capacitor **418** may be provided between the source **408a** and the gate **408b** of the transistor **408**. Likewise, the source **408a** (or drain **408c**) of the transistor **408** may be connected to its body substrate **408d**. The drain **408c** of transistor **408** may be connected to the source **410a** of transistor **410**. In addition, the source **410a** (or drain **410c**) of transistor **410** may be

connected to its body substrate **410d**. The drain **410c** of transistor **410** may be connected to the source **412a** of transistor **412**. Another external component such as a capacitor **420** may be positioned between the gate **412b** and the drain **412c** of transistor **412**. Further, the body substrate **412a** of the transistor **412** may be connected to the source **406a** of the transistor **406**. The drain **406c** of the transistor **406** may be connected to ground. As similarly described above, the transistor **406** may operate as a substrate body switch for transistor **412**.

A. Transmit Mode

FIG. **4B** illustrates an equivalent circuit of the receiver switch **404** in an OFF (e.g., disabled, block, etc) state, according to an example embodiment. In FIG. **1B**, the receiver switch **404** may be placed in the OFF state in order to provide isolation from the transmit switch **402**. With the receiver switch **404** in the OFF state, a transmit signal may be provided from a transmit (Tx) block to the antenna **400**. As shown in FIG. **4B**, when the receiver switch **404** is in an OFF state, the stacked transistors **408**, **410**, **412** may then be placed in an OFF state (e.g., opened), thereby providing a higher impedance. The stacked transistor **406** may be placed in an ON state **414** (e.g., closed), thereby shorting the substrate body **412d** of transistor **412** to ground, and reducing the signal paths for leakage current to travel from source **412a** to drain **412c**.

The power handling capability of the transmit switch transistor **402** may be dependent upon the performance of the receiver switch **404** in the OFF state. The allowance of a large voltage swing at the antenna **400** port, maintenance of high impedance of OFF-state receiver switch **404**, and disabling the substrate junction diodes in the receiver switch **404** for negative voltage swings may provide for high power handling capability of the CMOS antenna switch.

According to an example embodiment of the invention, large voltages swings at the antenna **400** port may be partially resolved using stacked transistors **408**, **410**, **412**, as provided for receiver switch **404**. Indeed, as similarly described above, the large voltage swings may be divided among the stacked transistors **408**, **410**, **412**. It will be appreciated that more than three stacked transistors may be utilized without departing from embodiments of the invention. Likewise, the impedance of the OFF-state receiver switch **404** may be improved by using the body switching technique described above. More specifically, with the body switching technique, the transistor **406** may be provided in an ON state, thereby connecting the body substrate **412d** of transistor **412** to ground, and reducing the signal paths for leakage current to travel from source **412a** to drain **412c**.

With respect to negative voltage swings experienced at the negative port, the CMOS RF antenna switch may utilize external components such as capacitors **418**, **420** to reduce leakage current by preventing channel formation of a transistor (e.g., transistors **408**, **412**) in the OFF state. The use of these external components such as capacitors **418**, **420** to reduce leakage currents in the OFF-state receiver switch **404** will now be discussed in further detail with respect to FIGS. **5** and **6**.

FIG. **5** illustrates an equivalent lumped model of a multi-stack structure of the receiver switch **404** of FIG. **4B**, according to an example embodiment of the invention. In FIG. **5**, the equivalent lumped model is provided for transistors **408**, **410**, **412** being in an OFF state with transistor **406** being in an ON state. As shown in FIG. **5**, the equivalent lumped model for transistor **408a** includes capacitors **502a**, **504a**, **506a**, and p-n junction diode **508a**. The equivalent lumped model for transistor **410** includes capacitors **502b**, **504b**, **506b**, and p-n junction diode **508b**. Likewise, the equivalent lumped model

for transistor **412** includes capacitors **502c**, **504c**, **506c**, **510**, and p-n junction diodes **508**, **512**.

It should be appreciated that the capacitances for capacitors **502a-c**, **504a-c**, and **506a-c** for the OFF-state transistors **408**, **410**, **412** may vary depending on the applied voltage swing, according to an example embodiment of the invention. Further, without the use of the external components such as capacitors **418**, **412**, it is possible that the OFF-state transistors **408**, **410**, **412** may not actually stay in the OFF state for all voltage swings at the antenna **400** port. Instead, when a high power signal is delivered from the Tx switch **402** to the antenna **400** port, the OFF-state switches transistors **408**, **410**, **412** may experience a large voltage swing at the antenna **400** port. In this situation, the OFF-state transistors **408**, **410**, **412** may turn ON, thereby causing undesirable leakage current may start to flow in the receiver switch **404**. This undesirable leakage current may deteriorate the performance of the transmit signal as well as destroy the LNAs and Mixers in the receiver (Rx) block. However, as will be described in further detail below with respect to FIG. **6**, the use of the external components such as capacitors **418**, **420** may prevent one or more of the OFF-state transistors **408**, **410**, **412** from turning ON.

FIG. **6** illustrates an equivalent circuit on an OFF-state CMOS transistor **600** such as OFF-state transistor **408**, **410**, according to an example embodiment of the invention. The OFF-state transistor **600** may be depicted using parasitic capacitors such as gate-drain capacitor C_{gd} **602**, gate-source capacitor C_{gs} **604**, body-source capacitor C_{bs} **606** and body-drain capacitor C_{bd} **608**. According to an embodiment of the invention, the OFF-state CMOS transistor **600** requires a zero bias **614** for the gate, drain, and source to stay in the OFF state. When a small signal **616** voltage swing is applied to the drain, the source and drain remain at about a zero bias so that the OFF-state transistor **600** does not turn on. However, if a large signal **618** voltage swing is applied to the drain, the negative cycle **620** of the large signal **618** voltage swing may result in the drain having a lower voltage potential than the gate so that a current **624** may flow from the source to the drain. During the positive cycle **622** of the large signal **618** voltage swing, the potential of the gate may be determined based upon the capacitances of the gate-drain capacitor C_{gd} **602** and the gate-source capacitor C_{gs} according to

$$V_g = V_d \left(\frac{C_{gd}}{C_{gd} + C_{gs}} \right).$$

With a voltage potential at the gate, a current **626** may flow from the drain to source.

In accordance with example embodiments of the invention, external components such as one or both of external capacitors **418**, **420** may be used to prevent undesirable currents **624**, **626** during the respective negative cycle **620** and positive cycle **622** of the voltage swings. In particular, according to an embodiment of the invention, an external component such as an external capacitor **420** may be connected between gate and drain such that the potential of gate is almost same as the drain so that the OFF-state transistor **600** does not turn on during the negative cycle **620** voltage swing. Likewise, an external component such as an external capacitor **418** may be connected between gate and source such that the potential of gate is almost same as the source so that OFF-state transistor **600** does not turn on during the positive cycle of voltage swing. Accordingly, by utilizing external components such as external capacitors **418**, **420**, the receiver switch **404** in accordance

with an embodiment of the invention may resolve this conflict demand for both negative **620** and positive cycle **622** of the voltage swing in the drain from the antenna **400** port.

In summary, the receiver switch **404** in the OFF-state may include stacked transistors **408**, **410**, **412** for dividing the voltage burden of each transistor for large voltage swings at the antenna **400** port. Additionally, the OFF-state receiver switch **404** may utilize a body switching technique **406** for stacked transistor **412** in order to maximize the OFF-state impedance and reduce the leakage currents. Finally, the external components such as external capacitors **418**, **420** may be added between either the source and gate or the drain and gate to prevent OFF-state devices of the receiver switch **404** from turning ON during a negative or positive voltage swing at the antenna **400** port.

B. Receive Mode

FIG. **4C** illustrates an equivalent circuit of the receiver switch **404** in an OFF (e.g., disable, block, etc.) state, according to an example embodiment of the invention. In FIG. **4C**, the receiver switch **404** may be placed in the ON position in order for the receive (RX) block to receive a signal from the antenna **400**. With the receiver switch **404** in the ON state, the transmit switch **402** may be placed in the OFF (e.g., disabled, block) state to isolate the transmit switch **402** from the receiver switch **404**. As shown in FIG. **4C**, when the receiver switch **404** is in an ON state, the stacked transistor **406** may be placed in an OFF state **416**, thereby providing an equivalent resistor between the body substrate **112d** of transistor **412** and ground (i.e., body floating). In this way, the insertion loss at the receive (Rx) path from the antenna **400** to the RX block may be minimized.

C. Variations of Capacitances/Impedances

FIG. **7** illustrates the variation of the overall capacitance in multi-stack structure as the input power increases in the drain port. The parasitic capacitor values (e.g., C_{gd} **602**, C_{gs} **604**, C_{bs} **606** and C_{bd} **608**) may vary depending on whether a transistor is in ON state or OFF state. If an OFF-state transistor in a receiver switch starts to turn ON by a large voltage swing supplied to the drain, then overall capacitance value of the OFF-state transistor may increase accordingly. As shown by capacitance **702** in FIG. **7**, a receiver switch that only utilizes body switching (e.g., FIG. **1B**), but not external components such as capacitors **418**, **420** in FIG. **4B**, may result in the receiver switch having a high capacitance **702** at a high input power. The high capacitance **702** may be indicative of OFF-state transistors in the receiver switch inadvertently turning ON. By contrast, by using body-switching and external components such as capacitors **418**, **420** in accordance with FIG. **4B**, a low capacitance **704** may be achieved even for a high input power. Accordingly, the low capacitance **704** at high input power means that the OFF-state transistors remain OFF even for a high input power. Accordingly, an OFF-state multi-stack receiver switch using both a body-switching technique and external components may be more stable than an OFF-state multi-stack receiver switch using only a body-switching technique.

FIG. **8A** and FIG. **8B** illustrates OFF-state impedance differences between a multi-stack receiver switch using a body-switching technique and a receiver switch using both the body-switching techniques and external components such as capacitors **418**, **420**. The variation of OFF-state impedance of a transistor switch of an OFF-state receiver switch may depend on the operating frequency as well as the level of input power. In particular, the operating frequency may change vary the impedance of parasitic capacitors (e.g., parasitic capacitors **602**, **604**, **608**, **610**) of the OFF-state transistor. The variation of the OFF state impedance of a receiver switch may

affect power handling capability and the harmonic performance at Tx switch. FIG. **8A** illustrates OFF-state impedances based upon a small signal simulation that is performed by sweeping frequencies with fixed input power. As shown in FIG. **8**, for a small signal simulation, the impedance **802** for a receiver switch using only a body-switching technique may be similar to the impedance **804** for a receiver switch using both the body-switching technique. However, the OFF-state impedances may be different from for a large signal simulation that sweeps input powers at a fixed frequency. In particular, as shown in FIG. **5B**, the impedance **806** of an OFF-state receiver switch using only body-switching may be lower at a higher input power than the impedance **808** of an OFF-state receiver switch using body-switching and external components. Accordingly, the receiver switch using body-switching and external components may have higher power handling capability and better harmonic performance.

III. Simulation Results

FIG. **9** illustrates simulation results for leakage currents in multi-band (e.g., 900 MHz, 1.9 GHz, 2.1 GHz) receiver switches in accordance with an example embodiment of the invention. As shown in FIG. **9**, the leakage current **902** of a multi-stack receiver switch using only body-switching may be significantly higher than the leakage current **904** of a multi-stack receiver switch using both body-switching and external components.

FIG. **10** illustrates simulation results for power handling capabilities for the multi-band transmit switches in accordance with an example embodiment of the invention. As shown in FIG. **10**, the power handling capability **1002** for a multi-stack receiver switch using only body-switching may be significantly worse for higher input powers than the power handling capability **1004** for a multi-stack receiver switch using both body-switching and external components.

FIG. **11** illustrates simulation results for the second harmonic performance for multi-band transmit switches in accordance with an example embodiment of the invention. As shown in FIG. **11**, the second harmonic performance **1102** for a multi-stack receiver switch using only body-switching may be worse than the second harmonic performance **1104** for a multi-stack receiver switch using both body-switching and external components.

FIG. **12** illustrates simulation results for the third harmonic performance for multi-band transmit switches in accordance with an example embodiment of the invention. As shown in FIG. **12**, the third harmonic performance **1102** for a multi-stack receiver switch using only body-switching may be worse than the third harmonic performance **1104** for a multi-stack receiver switch using both body-switching and external components.

Many modifications and other embodiments of the inventions set forth herein will come to mind to one skilled in the art to which these inventions pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the inventions are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

The invention claimed is:

1. A CMOS antenna switch, comprising:
 - an antenna operative at a plurality of radio frequency (RF) bands;
 - a transmit switch in communication with the antenna;

11

a receiver switch in communication with the antenna, wherein the receiver switch comprises a plurality of transistors;

a first external component provided for a first transistor of the plurality of transistors, wherein the first transistor includes a first source and a first gate, and wherein the first external component connects the first source and the first gate; and

a second external component provided for a second transistor of the plurality of transistors, wherein the second transistor includes a second gate, a second drain, and a second body substrate, wherein the second external component connects the second gate and the second drain, and wherein the second body substrate is selectively connectable between a resistance and ground.

2. The antenna switch of claim 1, wherein at least one of the first external component and the second component is a capacitor.

3. The antenna switch of claim 1, further comprising a body substrate switch for selectively connecting the second body substrate of the second transistor between a resistance and ground.

4. The antenna switch of claim 3, wherein during a transmit (Tx) mode, the transmit switch is enabled, the receiver switch is disabled, and the body substrate switch is enabled to connect the second body substrate to ground, thereby reducing leaking current toward a receiver (Rx) block associated with the receiver switch.

5. The antenna switch of claim 3, wherein the body substrate switch is operated in a first state to electrically connect the second body substrate to ground, and wherein the body substrate switch is in operated in a second state different from the first state to provide the resistance between the second body substrate and ground.

6. The antenna switch of claim 3, wherein the body substrate switch comprises a third transistor having a third source and a third drain, wherein the third source is electrically connected to the second body substrate of the second transistor and the third drain is electrically connected to ground.

7. The antenna switch of claim 3, wherein during a receive (Rx) mode, the transmit switch is disabled, the receiver switch is enabled, and the body substrate switch is disabled to provide the resistance between the second body substrate and ground.

8. The antenna switch of claim 7, wherein the second transistor includes a second source, wherein an equivalent circuit of the second transistor when the receiver switch comprises a drain-body capacitor connection and a body-source capacitor connection, and wherein while the receiver switch is enabled, at least a portion of a signal path for a receive signal from the antenna is formed by the drain-body capacitor connection and the body-source capacitor connection.

9. The antenna switch of claim 1, wherein the plurality of transistors comprise Complementary Semiconductor Oxide (CMOS) transistors that are cascaded together.

10. The antenna switch of claim 1, wherein the first transistor further includes a first drain and a first body substrate, and further comprising a third transistor having a third source, a third drain, and a third body substrate, wherein the first drain is connected to the second source and the second drain is connected to the third source.

11. A method for a CMOS antenna switch, comprising:
 providing an antenna operative at a plurality of radio frequency (RF) bands;
 electrically connecting a transmit switch and a receiver switch to the antenna, wherein the receiver switch comprises a plurality transistors;

12

providing a first external component for a first transistor of the plurality of transistors, wherein the first transistor includes a first source and a first gate, and wherein the first external component connects the first source and the first gate;

providing a second external component for a second transistor of the plurality of transistors, wherein the second transistor includes a second gate, a second drain, and a second body substrate, wherein the second external component connects the second gate and the second drain, and wherein the second body substrate is selectively connectable between a resistance and ground.

12. The method of claim 11, wherein providing the first external component and the second external component comprises providing at least one capacitor for the first external component or the second external component.

13. The method of claim 11, further comprising:
 providing a body substrate switch for selectively connecting the second body substrate between the resistance and ground.

14. The method of claim 13, wherein during a transmit (Tx) mode, the transmit switch is enabled, the receiver switch is disabled, and the body substrate switch is enabled to connect the second body substrate to ground, thereby reducing leaking current toward a receiver (Rx) block associated with the receiver switch.

15. The method of claim 13, wherein the body substrate switch is operated in a first state to electrically connect the second body substrate to ground, and wherein the body substrate switch is in operated in a second state different from the first state to provide the resistance between the second body substrate and ground.

16. The method of claim 13, wherein the body substrate switch comprises a third transistor having a third source and a third drain, wherein the third source is electrically connected to the second body substrate of the second transistor and the third drain is electrically connected to ground.

17. The method of claim 13, wherein during a receive (Rx) mode, the transmit switch is disabled, the receiver switch is enabled, and the body substrate switch is disabled to provide the resistance between the second body substrate and ground.

18. The method of claim 17, wherein the second transistor includes a second source, wherein an equivalent circuit of the second transistor when the receiver switch comprises a drain-body capacitor connection and a body-source capacitor connection, and wherein while the receiver switch is enabled, at least a portion of a signal path for a receive signal from the antenna is formed by the drain-body capacitor connection and the body-source capacitor connection.

19. The method of claim 11, wherein the plurality of transistors comprise Complementary Semiconductor Oxide (CMOS) transistors that are cascaded together.

20. The method of claim 11, wherein the first transistor further includes a first drain and a first body substrate, and further comprising a third transistor having a third source, a third drain, and a third body substrate, wherein the first drain is connected to the second source and the second drain is connected to the third source.

21. A CMOS antenna switch, comprising:
 an antenna operative at a plurality of radio frequency (RF) bands;
 a transmit switch in communication with the antenna;
 a receiver switch in communication with the antenna, wherein receiver switch comprises a plurality of transistors, including a first transistor having a first source and a first gate, and a second transistor having a second gate, a second drain, and a second body substrate;

13

means for electrically connecting the first source and the first gate;
means for electrically connecting the second gate and the second drain;

14

means for selectively connecting the second body substrate between a resistance and ground.

* * * * *